RUBBER LABORATORY

MARE ISLAND NAVAL SHIPYARD

TECHNICAL REPORT

SUBJECT

DEVELOPMENT OF DAMPING TREATMENTS FOR NEW CONSTRUCTION SUBMARINES

PROGRESS REPORT NO. 9

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DEVELOPMENT OF DAMPING TREATMENTS FOR NEW CONSTRUCTION SUBMARINES

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RUBBER LABORATORY

MARE ISLAND NAVAL SHIPYARD

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ABSTRACT

This work is a continuation of the development of damping treatments for submarines. Test treatments were applied to either one face, or to two faces of 1-3/4 inches thick steel bars, simulating in thickness bulkheads, and to 3/4 inch thick bars, simulating webs of deep frames. Each treatment consisted of a 1/8 inch thick constrained strip of wool felt, and a constraining aluminum bar.

Damping of vibrations induced in the bars increased with constraining pressure, attaining a maximum at about 20 to 65 psi, after which damping declined. The beneficial effect of the initially applied pressure persisted even after 103 days of stress relaxation. The effect of pressure is primarily attributed to the state of compression of the felt, rather than to pressure per se. This effect was more pronounced the higher was the weight ratio of the constraining layers to the steel bar. At a pressure of 50 psi average damping over the frequency range up to 2100 cps was proportional to this ratio.

The best treatments were No. 178A for 3/4 inch thick steel bars, and No. 170 for 1-3/4 inch bars. Their weight ratios were 0.46 and 0.40, respectively. Their average dampings at 85°F were 15% and 9% of critical, respectively, over the frequency range up to 2100 cps.

Treatments applied to only one side of a steel bar yielded the same, or slightly higher damping than treatments of equal weight ratio applied to two sides of a bar.

REFERENCES

(a) BUSHIPS ltr F013-13-01 Ser 634C1-837 of 16 May 1960

(b) NAVSHIPYD MARE Rubber Laboratory Report 94-12 of 19 Jul 1960;
"Development of Damping Treatments for New Construction Submarines
and Surface Ships, Progress Report No. 1"

(c) NAVSHIPYD MARE Rubber Laboratory Report 94-22 of 22 Aug 1960;
"Development of Damping Treatments for New Construction Submarines and
Surface Ships, Progress Report No. 2"

(d) NAVSHIPYD MARE Rubber Laboratory Report 94-23 of 26 Sep 1960;
"Development of Damping Treatments for New Construction Submarines and
Surface Ships, Progress Report No. 3"

(e) NAVSHIPYD MARE Rubber Laboratory Report 94-24 of 17 Nov 1960;
"Development of Damping Treatments for New Construction Submarines and
Surface Ships, Progress Report No. 4"

(f) NAVSHIPYD MARE Rubber Laboratory Report 94-25 of 30 Jan 1961;
"Development of Damping Treatments for New Construction Submarines and
Surface Ships, Progress Report No. 5"

(g) NAVSHIPYD MARE Rubber Laboratory Report 94-27 of 29 Mar 1961;
"Development of Damping Treatments for New Construction Submarines and
Surface Ships, Progress Report No. 6"

(h) NAVSHIPYD MARE Rubber Laboratory Report 94-29 of 14 Jun 1961;
"Development of Damping Treatments for New Construction Submarines and
Surface Ships, Progress Report No. 7"

(i) BUSHIPS ltr F013-13-01 Ser 634C1-736 of 21 Jul 1961

(j) NAVSHIPYD NYK ltr 948:WH:nt Lab Project 6062, Progress Report 26 of 2 Mar 1961

(k) BUSHIPS ltr F013-13-01 Ser 63401-1476 of 10 Oct 1960

(l) Torque Manual, P. A. Sturtevant Co., 2nd Edition, 1957

INTRODUCTION

1. The work described herein is a continuation of the project for developing vibration-damping treatments for pressure bulkheads and webs of deep hull frames of submarines. This investigation was authorized by the Bureau of Ships in reference (a).

2. The results obtained in the previous stages of the work were reported in references (b) through (h). That work dealt with damping treatments for thick (1-3/4 inch) bulkheads only. The treatments investigated were all of the constrained layer type. The constrained layers were usually wool felt or rubber, and the constraining layers were usually aluminum or steel. All of these treatments were intended for application to both faces of the bulkhead.

3. The best damping treatments for pressure bulkheads found in the prior work were Treatments 129 and 170. These treatments were capable of yielding at 85°F an average damping efficiency of 10% of critical damping over a frequency range of 50 to 1500 cps. Both of these treatments comprised a constrained layer of 1/8 inch thick treated wool felt and a constraining layer of 1 inch thick aluminum plate on both faces of the bulkhead. The ratio of the weight of the two aluminum plates to the weight of the steel

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bulkhead was 0.40.   The studs which held the aluminum plates to the
bulkheads were spaced 11 inches apart in both treatments.   Treatment 129
had 1/4 inch diameter studs; Treatment 170 had 5/8 inch diameter studs.

OBJECTIVES

4.   The work reported herein was a continuation of the study of damping
treatments consisting of constrained layers of 1/8 inch thick treated wool
felt and constraining layers of aluminum plate.   The objectives were to
investigate the following:

   a.   General effect of constraining pressure on damping efficiency.
        It was shown in Report 94-29, reference (h), that increasing the
        constraining pressure improved damping efficiency until a limiting
        value was reached.

   b.   Effect on damping of relaxation of constraining pressure.

   c.   Effect of stud spacing and stud size.

   d.   Effect of thickness of aluminum constraining layer.

   e.   Effect of location of damping treatment, i. e., all on one side
        of damped plate or divided between both sides.

   f.   Choice of treatments for damping 3/4 inch thick steel plates as
        well as for damping 1-3/4 inch thick steel plates.

5.   The work described in this report was started before receipt of the
Bureau's instructions in reference (i) concerning future work on this
project.   Consequently, in this work no limitation was placed on the weight
of the damping treatment.

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DESCRIPTION OF DAMPING TREATMENTS

6. The tested treatments are described in Appendices 1 and 2. Each one of the tested treatments consisted of a wool felt layer 1/8 inch thick, and an aluminum plate which was used as a constraining layer. The treatments were applied to flat steel bars, 3/4 inch or 1-3/4 inch thick. Most of the treatments were applied to both flat sides of the steel bar. Three treatments were applied to only one side of the bar.

7. The aluminum constraining plates varied in thickness from 1/8 inch to 1 inch, depending on the treatment. The felt layer used with each constraining layer consisted of two plies of 1/16 inch thick strips. The felt was procured under Stock No. G5330-196-8816 of Navy Stock List of General Stores, and conformed to specification MIL-G-20241B. It was impregnated with a non-drying, non-oxidizing, anticorrosive chromated compound, and coated on one side with a thin film of pressure-sensitive adhesive compound.

8. The aluminum constraining bars were fastened to the steel bars by means of studs, nuts and washers. Quarter-inch, 1/2 inch, or 5/8 inch diameter studs were used, and the distances between the studs varied from 3 to 12 inches, depending on the treatments. A stud spacing of 3 inches is manifestly unsuitable for practical applications. This spacing was used in the present work because it served to indicate whether stud spacing per se influenced damping, and also because it enabled the application of high constraining pressures, up to 100 psi, to thin constraining layers without causing significant bulging.

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9. The weight ratios of the constraining aluminum layers to the steel bars varied between 0.12 and 0.46. This ratio is based on the total weight of the constraining layer or layers of each treatment, whether applied to one side or to two sides of a steel bar. The ratio does not include the weights of the felt layers, the studs, the nuts, or the washers. The weight of the 1/8 inch thick felt was 0.3 lb. per square foot. The combined weights of the studs, nuts, and washers per square foot of treatment area was from 0.1 to 0.5 lb., depending on the treatment.

TESTING PROCEDURES

10. The testing procedures were essentially the same as those which were reported in reference (h). They are described in detail in Appendix 3. The instrument arrangement for determining damping is shown in Appendix 4. It differed in one important aspect from the arrangement of reference (h), namely, the substitution of a one-octave Spencer Kennedy Laboratories, Model 302 filter for the half-octave filter used in the work of reference (h). The one-octave filter permitted the determination of damping up to approximately 20% of critical damping. The upper working limit for the half-octave filter was about 12-15% of critical damping. Damping was determined at 85°F, unless otherwise stated.

11. Appendix 3 also describes and discusses the procedures for determining the constraining pressure on the felt layer, the thickness of the compressed felt layer, the detection and measurement of the bulge in the constraining layer caused by the applied pressure, the screening of the modes of vibration.

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PRESENTATION OF DAMPING DATA

12. For each variant tested in this work the damping, expressed as per cent
of the critical damping, was determined for the resonance frequencies of the
bar assembly up to a frequency of about 3000 cps. These determinations were
then repeated twice or thrice without changing the felt strips or the con-
straining pressure, and the damping values were averaged for each resonance
frequency, as well as for the entire frequency range up to the resonance
frequency nearest to 2100 cps. There were from 10 to 13 resonance frequencies
in this range, and each average damping value for this entire range was the
average of some 30 to 50 measured values.

13. This manner of presenting average damping differs slightly from the manner
in which average damping was presented in the previous work, as reported in
reference (h). In that reference average damping was calculated only for
the frequency range up to 1500 cps. The justification for the selection of
this range was the finding that no substantial damping was observed in that
work beyond about 1500 cps, even in treatments which yielded the highest
damping values. It was also observed in such treatments that damping fell
off very sharply above frequencies of about 1300-1500 cps. For this reason
it was assumed that 1500 cps represented the approximate limit for effective
damping of the tested treatments. In the present work the improved technique
of determining damping resulted in a shift of that limit to about 2100 cps.
This limit is presumably inherent in the properties of the felt material
used at the test temperature, 85°F. Thus, the choice of 2100 cps as the
upper frequency limit for reporting average damping was not arbitrary. It

should be noted that the relations between damping and constraining pressure, or weight ratio of constraining layer to steel bar were essentially the same, regardless as to whether average damping up to 1500 cps, or up to 2100 cps was used.

14. An additional reason for the choice of this limit is based on the following consideration: practically all of the modes of the flexural vibration series studied up to about 1900 to 2200 cps could be observed and identified. Beyond these frequencies however, wide gaps existed between consecutive modes, and the identification of these modes became uncertain.

15. The frequency range for each test variant in which damping was equal or greater than 5% of critical was determined. These data were tabulated and plotted. The plots of damping versus frequency tended to be smooth, and in most instances were free of sharp zigzags. Consequently, each plot usually contained only one continuous band of frequencies in which damping was above 5% of critical. For this reason the width of this band is considered to be a convenient and a useful parameter for evaluating the damping characteristics of the treatments.

16. Some 50 variants were tested in this work. The average damping up to 2100 cps, and the frequency range in which damping was equal to or exceeded 5% of critical, were tabulated for each varient. Some of these data were also plotted. The damping values obtained at each resonance frequency were not tabulated, but such data were plotted for a selected number of variants to illustrate significant aspects of the treatments. It is felt that presentation of such plots for all of the studied variants would not have contributed

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to clarity of exposition.

RESULTS

Precision of Damping Measurements

17.   The degree of precision of the damping values which were obtained in this work can be gauged from the data of Appendix 5. The appendix presents the damping values obtained in two typical tests in which four, consecutive, duplicate runs were made in each test. The same assemblies were used in each test, and no torque adjustments were made between runs. Large variations in damping values, up to 7% of critical, were encountered in replicate determinations. Very much smaller variations, however, were found between the damping averages of replicate runs for the frequency range up to 2100 cps. In the case of Treatment 178A, the average deviation of these averages from the mean of the four runs of this treatment was 0.1% of critical damping. The corresponding deviation for Treatment 179A was 0.2% of critical damping. The respective frequencies at which the bars resonated in these replicate determinations did not vary more than a few per cent between determinations.

18.   These findings attest to the relatively high degree of precision of the average damping values used in this work. They also strongly suggest that the much larger fluctuations between the damping values for individual vibrational modes were mainly due to random-type errors, rather than to biased-type errors. These errors were largely cancelled out by averaging the damping values over the wide frequency range. The random-type errors were presumably due mainly to errors in locating the resonance frequencies, in

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measuring the angle of the attenuated signal in the Memoscope, and in the selection of the proper portion of the oscilloscope tracing for measuring the angle. The latter type of error was more likely to occur when the signal had beats.

19. The reproducibility of the data obtained in this work was not as good as might be presumed from the degree of precision for average damping shown in Appendix 5. The data of this appendix were obtained in replicate runs in which the same assemblies were used. When, however, replicate assemblies of the same treatment were tested, additional sources of error were introduced, which resulted in wide variations in the values for average damping. This behavior is demonstrated by the data of Appendix 2 for Treatment 179A. Average dampings obtained in tests on two assemblies of an initial constraining pressure of 4 psi were 6.5% and 3.8%, respectively. Average dampings obtained at a pressure of 38 psi were 9.2% and 5.2%, respectively.

20. Part of these deviations might have been due to unequal compressions of the two sets of felt strips in replicate test assemblies when the same pressure was applied. This inequality is indicated by the wide variations in the thicknesses of the compressed felt layers in replicate tests. But this factor alone is inadequate to account for the observed variations, since a plot of average damping against felt thickness did not result in a smooth curve. The cause of the encountered variations in average damping has not been determined as yet. The suggestion is ventured, however, that differences in the textures of felt strips in the replicate assemblies might have been at least partly responsible for these variations.

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Effect of Constraining Pressure on Damping

21.   The relations between damping and the constraining pressures applied
to the treatments are indicated by the data of Appendices 1 and 2. As a
general rule, average damping and the width of frequency band over which
damping was in excess of 5% of critical increased with constraining pressure
up to maximum values at pressures of about 20 to 65 psi, depending on the
treatment. Beyond these pressures damping decreased. The effect of pressure
was most pronounced in Treatment 178A, which exhibited the highest damping
of all of the tested treatments. The relations between damping and constrain-
ing pressures for Treatments 178A and 170 are shown in Appendices 6, 7, and 8.

22.   There were a few exceptions to this rule. The widest discrepencies were
observed in the case of Treatment 179A. They were due in part to the fact
that the data for this treatment were obtained from two separate test
assemblies, as was explained in paragraph 20. A single test assembly was
used for each of the other treatments listed in Appendices 1 and 2.

23.   The decline in damping which occurs at high constraining pressures was
not observed in the previous work, reference (h). This is attributed to the
use of a half-octave filter in that study. This filter was inadequate for
measuring damping in excess of 12% or 15% of critical. The one-octave filter
which was employed in the present work was suitable for measuring damping up
to about 20%. The more accurate data obtained with this filter enabled
detection of the damping decline.

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24.   In the previous work, reference (h), it was recommended that a constrain-
ing pressure of 50 to 100 psi be applied to the treatment at the time of its
installation aboard ship. The more extensive tests made in the present work
indicate that higher average damping and wider frequency range over which
damping is in excess of 5% of critical will be obtained at pressures in the
range of 20 to 40 psi. A pressure of 30 psi would seem to be adequate for
practical applications. This reduction in pressure will enable the use of
wider spacings between studs than at the previously recommended higher
constraining pressures, before reaching the critical pressure limit beyond
which significant bulging of the constraining layer will occur. Pressure
is to be applied by means of a torque wrench to the desired level according
to the equation of paragraph 9 of Appendix 3. It is further recommended that
the application of pressure be repeated thrice, with no less than one hour
between each application.

25.   It was shown in reference (h) that when the damping efficiency of the
treatment was increased by raising the constraining pressure, the improve-
ment in damping persisted even after considerable lowering of this pressure
due to stress relaxation of the felt layer. This suggested that pressure
per se was not important in increasing damping, but that the effect of
pressure was indirect, and was due to the compression of the felt layer.

26.   It is apparent from Appendices 1 and 2 that damping tended to increase
as the felt layer was progressively compressed, until maximum damping was
reached at a felt thickness of about 0.070 to 0.090 inch, depending on the
treatment. Further compression of the felt resulted in a decrease in damping.

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Available data suggest that practically all of the air interstices in the felt were removed at a constraining pressure of 100 psi. On this assumption the volumes of the air in the felts at constraining pressures corresponding to maximum damping were calculated for the various treatments by means of the equation of paragraph 19 of Appendix 3. These volumes ranged from about 10% to 20% of the volume of the compressed felt. The volume of air in the non-compressed felt was about 40% to 50%. It is concluded, therefore, that the reduction in damping at high constraining pressures was associated with curtailment of the freedom of movement of the felt fibres.

Effect of Relaxation of Constraining Pressure on Damping

27. As stated in paragraph 25, the data of reference (h) showed that the benificial effect of pressure on damping persisted even after a substantial reduction of the initially applied pressure due to stress relaxation. In that work the damping measurements were made within a short period of about one hour to a few days after application of the constraining pressure. Under service conditions the compressed felt in a damping treatment will be under-going stress relaxation over a very protracted period. It was of interest, therefore, to determine the extent of the preservation of the benificial effect of pressure over long periods of time.

28. Treatments 170 and 178 were studied in this respect. A pressure of 65 psi was applied to Treatment 170 attached to a 1-3/4 inch thick steel bar, and a pressure of 19 psi was applied to Treatment 178 attached to a 3/4 inch thick bar. The assemblies were then let stand at room temperature. The residual torque was measured periodically and the residual pressure on the

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treatments was computed from these values by means of the equation of paragraph 9 of Appendix 3. Damping measurements were then made on the bars at 85°F after conditioning the assemblies for one day or for several days at this temperature. These measurements were made 63 and 103 days after application of pressure in the case of Treatment 170, and 14 and 52 days in the case of Treatment 178. The results are plotted in Appendices 9 and 10.

29. There was no significant change in the average damping of Treatment 178 over the frequency range up to about 2100 cps. During the 38-day period between the two tests of this treatment average damping was merely reduced from 11.7% to 11.3% of critical.

30. In the case of Treatment 170 average damping was determined for the frequency range up to about 1500 cps, since insufficient data were available for the frequency interval between 1500 cps and 2100 cps. Average damping over a period of 40 days fell off from 13.6% to 10.4%, a reduction of 3.2%. This change in damping might lie within the range of experimental errors.

31. In both treatments average damping was about 10% at the end of the long conditioning period, despite the fact that the residual constraining pressure at that time was reduced to about half of its initial value. It is concluded that in practical applications there will be no need to adjust the constraining pressures of the treatments, provided the initially applied pressure be sufficiently high, say 30 psi.

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Effect of Stud Diameter and Spacing on Damping

32. Treatments 129, 129A, and 170 were identical, except for stud diameters and spacings. All three treatments utilized 1 inch constraining layers of aluminum which were applied to 1-3/4 inch thick steel bars. Substantially the same dampings were obtained with the three treatments at comparable constraining pressures. Thus, stud spacing or stud diameter exerted no significant effect on damping.

33. It should be emphasized that stud diameter and spacing determine the critical constraining pressure beyond which significant bulging of a given constraining layer will occur. Bulging tends to reduce the damping efficiency of the type of treatments used in this work, as was shown in reference (h). From this point of view stud diameter and spacing may have a significant effect on damping, and these factors should be taken into consideration in practical applications.

34. It was recommended in paragraph 24 that a constraining pressure of about 30 psi be applied to damping treatments under service conditions. No systematic study was undertaken as yet to determine the critical pressures for bulging for constraining layers of different thicknesses, and for studs of varying diameters, placed at varying distances apart, but the information which has been obtained to date indicates that at a pressure of 30 psi, and with studs placed 12 inches apart, bulging will occur in 1/2 inch thick aluminum plates as well as in 7/32 inch thick steel plates. Under the same conditions bulging will occur, of course, in thinner plates of the same material. A spacing of about 6 inches between studs might

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prevent bulging of 1/2 inch thick aluminum plates at a constraining pressure of 30 psi. At this spacing 30 psi would be close to the critical bulging pressure of such plates. Studs 1/4 inch in diameter could be used for such installations, and a torque of 55 inch-lbs would yield the desired constraining pressure. This torque value was calculated from the equation of paragraph 9 of Appendix 3.

35. For the 1 inch thick aluminum layer, 1/2 inch diameter studs, placed 12 inches apart, could be used. A torque of 430 inch-lbs would produce a constraining pressure of 30 psi. No significant bulging of the constraining layer is expected under these conditions. Quarter-inch diameter studs could not be used with 12-inch spacing, because the required torque for 30 psi pressure would exceed the strength of the studs.

Effect of Thickness of Constraining Layer on Damping

36. Dampings at comparable constraining pressures were dependent on the thickness of the constraining layers. This was true for 3/4 inch thick steel bars, as well as for 1-3/4 inch thick bars. Thus, in the case of 1-3/4 inch thick aluminum constraining layers, the maximum average damping, for Treatments 129A and 170 were 8.4% and 9.3%, respectively. The corresponding value for Treatment 178C, which utilized 1/2 inch thick aluminum layers, was 6.6%. The effect was even more pronounced in the case of the 3/4 inch steel bars. In this instance the highest average damping obtained with Treatment 178A, which utilized 1/2 inch thick constraining layers, was 15.2%. The highest average damping obtained with Treatments 179A and 179B, in which 1/4 inch aluminum layers were used, was 9.2%.

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37. Analysis of the data of Appendices 1 and 2 revealed that the important factor in the relation between damping and thickness of constraining layer was not the thickness per se, but rather the weight or thickness ratio of the constraining layers to the steel bar. As an example, the damping obtained with 1/2 inch aluminum layers applied to a 3/4 inch steel bar (Treatment 178A) was about twice as large as the damping obtained with 1/2 inch aluminum layers applied to a 1-3/4 inch bar (Treatment 178C) at comparable constraining pressures.

38. This relation is further illustrated in Appendix 11. Average dampings at a constraining pressure of 50 psi of all of the treatments of Appendices 1 and 2 for which such data were available were plotted against the corresponding weight ratios. In computing this ratio the total weight of the aluminum layers was considered, irrespective of whether it was distributed on one face or on two faces of the steel bar. The plot of Appendix 11 indicates a near proportionality of damping to weight ratio. This plot might serve as a guide for estimating the potential damping capacities at 85°F of treatments consisting of aluminum constraining layers and 1/8 inch thick chromated felt, of the type used in this work.

Effect of Location of Treatment on Damping

39. A series of tests was made in which the dampings obtained with treatments applied to one side of the steel bar were compared with the dampings by treatments applied to two sides of the steel bar. In these comparisons the weight of the aluminum constraining layer of the one-sided application was equal to the combined weights of the two constraining layers of the

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two-sided application. Steel bars 3/4 inch thick were used in all tests. The thicknesses of the constraining layers ranged from 1/8 inch to 1/2 inch. The weight ratios of aluminum to steel was either 0.12 or 0.23. In each case the one-sided and the corresponding two-sided treatments were applied to the same steel bar, utilizing the same studs and stud spacing. Damping was determined at 85° or at 95°F. The treatments are further described in Appendix 2, which also contains the results of the tests.

40. In each instance, except one, the one-sided treatments had a slightly higher average damping than the corresponding two-sided treatment. The one exception was Treatment 192 compared to Treatment 195. Average damping for the two-sided Treatment 192 was 4.8%, versus 4.6% for the one-sided Treatment 195. The difference of 0.2% between the average damping of the two treatments is considered to be insignificant.

41. Little or no bulging was encountered in the one-sided treatments, while all but one of the two-sided treatments, Treatment 179A, exhibited appreciable bulging. The lower dampings of the two-sided treatments is in part attributed to bulging, particularly where bulging was very pronounced. This factor, however, is inadequate to account for all of the observed differences in damping. It is concluded that in the absence of bulging one-sided treatments would yield substantially the same damping as two-sided treatments of the same weight ratio of aluminum to steel.

Choice of Best Damping Treatments

42. The best treatment for 3/4 inch thick steel bars was Treatment 178A, which utilized a constrained layer of 1/8 inch thick chromated felt and a constraining layer of 1/2 inch thick aluminum. This treatment was applied to the two faces of the steel bar. Its weight ratio of aluminum to steel was 0.46, and it utilized 5/8 inch diameter studs, spaced 5-1/2 inches apart. Its average damping at a constraining pressure of 19 psi was 15%, and the frequency range over which damping was in excess of 5% extended from 50 to 1600 cps.

43. The best treatment for 1-3/4 inch thick steel bars was Treatment 170. It consisted of a constrained layer of 1/8 inch thick chromated felt, and a constraining layer of 1 inch thick aluminum. The treatment was applied to the two faces of the steel bar. Its weight ratio of aluminum to steel was 0.40, and it utilized 5/8 inch diameter studs, spaced 11 inches apart. Its overage damping at a constraining pressure of 40 psi was 9%, and the frequency range over which damping was in excess of 5% extended from 150 to 2100 cps.

SUMMARY

44. Tests conducted at 85°F on 3/4 inch and 1-3/4 inch thick steel bars with damping treatments consisting of a constrained layer of 1/8 inch thick chromated felt and a constraining layer of aluminum, which was varied in thickness from 1/8 inch to 1 inch, yielded the following results.

    a. Average damping over the frequency range between 50 and 2100 cps increased with rising constraining pressure up to a maximum, which

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was reached at pressures between 20 and 65 psi. The frequency range over which damping was in excess of 5% of critical exhibited the same trend.

b. The effect of constraining pressure on damping was not due to pressure per se, but rather to the state of compression of the constrained felt layer.

c. Treatments with a compressed felt layer exhibited high damping even after 100 days from the time pressure had been applied.

d. Average damping at a constraining pressure of 50 psi was proportional to the weight ratio of the aluminum constraining layers to the steel bar. This weight ratio is based on the total weight of the constraining layer or layers regardless of, whether applied to one face, or to the two faces of the steel bar.

e. The highest damping of 3/4 inch thick steel bars was obtained with Treatment 178A, which utilized 1/2 inch thick aluminum layers applied to two faces of a steel bar. The weight ratio for this treatment was 0.46. Average damping of 15% was obtained over the frequency range of 50 to 2100 cps. The corresponding frequency range over which damping was in excess of 5% extended from 50 to 1600 cps.

f. The highest damping of 1-3/4 inch thick steel bars was obtained with Treatment 170, which utilized 1/2 inch thick aluminum layers applied to two faces of a steel bar. The weight ratio of this treatment was 0.40. Average damping up to 9% was obtained over the frequency range from 50 to 2100 cps. The corresponding frequency range over which damping was in excess of 5% extended from 150 to 2100 cps.

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g. Tests made at 85° and 95° indicate that treatments applied only to one side of the steel bar yielded approximately the same, or slightly higher damping than treatments of the same weight ratio which were applied to two sides of the bar.

FUTURE WORK

45. The data obtained to date suggest several possibilities for improving the damping treatments of the type investigated in this work. The data also leave a number of unresolved problems of practical importance. A study of the following types of treatments seems promising.

One-Sided Treatments

46. The use of treatments applied to only one side of plates instead of treatments applied to two sides of plates will result in great savings in time and labor. One-sided treatments are also suitable for submarine parts which are not readily accessible to two-sided applications. It is believed that one-sided treatments would make it possible to obtain satisfactory damping on 3/4 inch thick steel plates with constraining layers of aluminum of relatively low weight ratios, and still avoid bulging. Two-sided treatments of the same weight ratio and stud spacing would be more prone to bulging.

Treatments Utilizing Various Types of Constrained Layers

47. Treatments utilizing constrained layers of felt or mattings of materials such as Nylon, Acrylon, and wool free of adhesive, should be investigated. Preliminary data show that the damping efficiency of the felt material used

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in the present study is very markedly reduced when the temperature is raised from 74° to 120°F. It is possible that the damping efficiency of some of the fibrous materials suggested above might not be susceptible to such wide changes in the temperature interval between 70° and 120°F.

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APPENDICES

DESCRIPTION OF DAMPING TREATMENTS INSTALL TEST BARS AND RESULTS OF TESTS

Steel feet bas wide
Constrained 1 wool felt
Stud location steel bar,
unless
Treatment loel bar
Test tempera

Treatment No.	Thickness of Each Aluminum Constraining Layer inch	Weight Ratio Aluminum (nominal) Aluminum to Steel	Studless of Compressed Diameter inch	Average Damping up to 2100 cps % of critical	Frequency Range for Damping above 5% of critical cps
129	1	0.40	1/4	.00 5.6	50- 350(700)**
				.92 6.4	50-1450
				.84 8.4	50-2100
129A	1	0.40	1/4	.92 6.9	50-1500
				.87 7.6	50-2100
				.78 7.6	150-1600(2100)**
				.71 8.4	150-2100
				.67 8.1	300-2100
				.65 7.1	300-1700
170	1	0.40	5/8	.97 5.4	50- 350
				.86 6.1	50-1200
				.74 8.7	150-2100
				.65 9.3	150-2100
				.60 6.8	150-1450
178C	1/2	0.20	1/4	.107 5.3	150-1200
				.100 5.6	150-1250
				.093 6.2	150-1250(1850)**
				.089 6.6	150-1900
				.083 5.4	250-1650
				.072 4.3	450-1150

* The thickness of the compressed felt was essentially the same; no significant bulging occurred in the constraining layer.

** Number in parentheses indicates that at or near this rate or slightly greater than 5% of critical.

*** Studs were arranged in two rows, 3 inches between studs; 2 to or 1-1/2 inches from an edge of the steel bar.

1

Steel test bars: 96 inches long x 6 in
Constrained layer: 1/8 inch thick tre
Stud location: One row along middle of
    unless otherwise indicated
Treatment location: On both faces of
Test temperature: 85°F

Treatment No.	Thickness of Each Aluminum Constraining Layer inch	Weight Ratio (nominal) Aluminum to Steel	Studs		Initial Constraining Pressure psi	Thi Co F
			Diameter inch	Spacing inches		
129	1	0.40	1/4	11	3 7 16	
129A	1	0.40	1/4	3***	11 22 50 65 87 109	
170	1	0.40	0.40	11	3 7 20 40 65	
178C	1/2	0.20	1/4	3***	7 11 15 25 50 100	

*   The thickness of the compressed felt was essentially uniform in all treatments constraining layer.

**   Number in parentheses indicates that at or near this frequency, damping was equ

*** Studs were arranged in two rows, 3 inches between studs in each row. Each row

(Page 1 of 2)

Steel test bars: 96 inches long x 6 inches wide
Constrained layer: 1/8 inch thick treated wool felt
Stud location: One row along middle of steel bar,
     unless otherwise indicated
Treatment location: On both faces of steel bar
Test temperature: 85°F

Weight Ratio (nominal) Aluminum to Steel	Studs		Initial Constraining Pressure psi	Thickness of Compressed Felt* inch	Average Damping up to 2100 cps % of critical	Frequency Range for Damping above 5% of critical cps
	Diameter inch	Spacing inches				
0.40	1/4	11	3	0.100	5.6	50- 350(700)**
			7	0.092	6.4	50-1450
			16	0.084	8.4	50-2100
0.40	1/4	3***	11	0.092	6.9	50-1500
			22	0.087	7.6	50-2100
			50	0.078	7.6	150-1600(2100)**
			65	0.071	8.4	150-2100
			87	0.067	8.1	300-2100
			109	0.065	7.1	300-1700
0.40	5/8	11	3	0.097	5.4	50- 350
			7	0.086	6.1	50-1200
			20	0.074	8.7	150-2100
			40	0.065	9.3	150-2100
			65	0.060	6.8	150-1450
0.20	1/4	3***	7	0.107	5.3	150-1200
			11	0.100	5.6	150-1250
			15	0.093	6.2	150-1250(1850)**
			25	0.089	6.6	150-1900
			50	0.082	5.4	250-1650
			100	0.072	4.3	450-1150

*   ...ressed felt was essentially uniform in all treatments since no significant bulging occurred in the

** ...icates that at or near this frequency, damping was equal to or slightly greater than 5% of critical.

*** ...o rows, 3 inches between studs in each row. Each row was 1-1/2 inches from an edge of the steel bar.

Steel test bars: 96 inches long x 6 i
Constrained layer: 1/8 inch thick tre
Stud location: One row along middle c
    unless otherwise indicated
Treatment location: On both faces of
Test temperature: 85°F

Treatment No.	Thickness of Each Aluminum Constraining Layer inch	Weight Ratio (nominal) Aluminum to Steel	Studs		Initial Constraining Pressure psi	Thi Co F
			Diameter inch	Spacing inches		
178D	1/2	0.20	1/4	11	1.6 3.2	
179C	1/4	0.10	1/4	3***	50 100	

*   The thickness of the compressed felt was essentially uniform in all treatments s
    constraining layer.
*** Studs were arranged in two rows, 3 inches between studs in each row. Each row wa

(Page 2 of 2)

Steel test bars: 96 inches long x 6 inches wide
Constrained layer: 1/8 inch thick treated wool felt
Stud location: One row along middle of steel bar,
    unless otherwise indicated
Treatment location: On both faces of steel bar
Test temperature: 85°F

Weight Ratio (nominal) Aluminum to Steel	Studs		Initial Constraining Pressure psi	Thickness of Compressed Felt* inch	Average Damping up to 2100 cps % of critical	Frequency Range for Damping above 5% of critical cps
	Diameter inch	Spacing inches				
0.20	1/4	11	1.6	0.112	5.0	50- 350
			3.2	0.106	5.4	50-1200
0.10	1/4	3***	50	--	2.8	none
			100	--	2.4	none

essed felt was essentially uniform in all treatments since no significant bulging occurred in the

rows, 3 inches between studs in each row. Each row was 1-1/2 inches from an edge of the steel bar.

Steel test bars: 68 inches long, and either 3
Constrained layer: 1/8 inch thick treated woo
Stud location: One row along middle of steel

Treatment No.	Location of Treatment on Steel Bar	Thickness of Each Aluminum Constraining Layer, inch	Weight Ratio (nominal) Aluminum to Steel	Studs Diameter inch	Spacing inches	Initial Constraining Pressure psi
178A	on both faces	1/2	0.46	5/8	5-1/2	2
						4
						8
						13
						19
						50
						100
179A	on both faces	1/4	0.23	5/8	5-1/2	4
						4
						8
						15
						19
						38
						38
179B	on both faces	1/4	0.23	1/4	3***	50
179A	on both faces	1/4	0.23	5/8	5-1/2	19
184	on both faces	1/2	0.23	5/8	5-1/2	19
185	on both faces	1/8	0.12	1/4	3	50

rs: 68 inches long, and either 3-5/8 inches or 4 inches wide
ayer: 1/8 inch thick treated wool felt
: One row along middle of steel bar

2

Studs		Initial Constraining Pressure psi	Thickness of Compressed Felt inch	Average Damping up to 2100 cps % of critical	Frequency Range for Damping above 5% of critical cps	Bulging of Constraining Layer inch	Test Temperature °F
Diameter inch	Spacing inches						
5/8	5-1/2	2	0.114	7.6	50-1000	none	85
		4	0.107	7.9	50-1700	none	
		8	0.103	11.5	50-1750	none	
		13	0.098	13.4	50-1850	none	
		19	0.093	15.2	50-1600	none	
		50	0.080	11.9	50-1000 (1500-1850)*	none	
		100	0.073	12.1	150-1900	none	
5/8	5-1/2	4	0.110	6.5	50- 600 (1200)**	none	85
		4	0.099	3.8	50- 200	none	
		8	0.094	4.8	100- 600	none	
		15	0.087	4.8	200- 800	none	
		19	0.095	5.5	100-1200 (1500)**	none	
		38	0.088	9.2	100-2050	none	
		38	0.078	5.2	200-1750	none	
1/4	3***	50	0.076	7.2	100-1200		85
5/8	5-1/2	19	0.095	6.0****	100-1200 (1500)**	none	85
5/8	5-1/2	19	--	6.4****	50-1050	none	85
1/4	3	50	--	3.5	none	0.006	85

Steel test bars: 68 inches long, and e
Constrained layer: 1/8 inch thick tree
Stud location: One row along middle of

Treatment No.	Location of Treatment on Steel Bar	Thickness of Each Aluminum Constraining Layer, inch	Weight Ratio (nominal) Aluminum to Steel	Studs		Initia Constrai Pressu psi
				Diameter inch	Spacing inches	
186	on both faces	1/4	0.12	1/4	3	50
192	on both faces	1/4	0.23	1/4	12	7
195	on one face	1/2	0.23	1/4	12	7
192	on both faces	1/4	0.23	1/4	12	21
195	on one face	1/2	0.23	1/4	12	21
192	on both faces	1/4	0.23	1/4	12	35
195	on one face	1/2	0.23	1/4	12	35

*   Damping near the 1300 cps frequency was about 1% of critical, but was otherwise
**   Number in parentheses indicates that damping at or near this frequency was equal
***   Studs were arranged in two rows, 3 inches apart, and 3 inches between studs in
****   Average damping for the frequency range of 50-1500 cps only, because data beyond

...rs: 68 inches long, and either 3-5/8 inches or 4 inches wide
...ayer: 1/8 inch thick treated wool felt
...: One row along middle of steel bar

Studs Diameter inch	Spacing inches	Initial Constraining Pressure psi	Thickness of Compressed Felt inch	Average Damping up to 2100 cps % of critical	Frequency Range for Damping above 5% of critical cps	Bulging of Constraining Layer inch	Test Temperature °F
1/4	3	50	—	4.3	350-1400	none	85
1/4	12	7	—	4.8	50- 600	0.013	95
1/4	12	7	—	4.6	50- 300	0.002	95
1/4	12	21	—	4.7	100- 650 (1300)**	0.026	95
1/4	12	21	—	5.6	50-1100	0.004	95
1/4	12	35	—	4.9	200-1050	0.028	95
1/4	12	35	--	5.9	100-1100	0.006	95

...critical, but was otherwise above 5% in the frequency range of 50-1850 cps.
...ear this frequency was equal to or slightly greater than 5% of critical.
...3 inches between studs in each row. Each row was 1-1/2 inches from an edge of the steel bar.
...ps only, because data beyond this range were unreliable.

APPENDIX 3

DETAILS OF TESTING PROCEDURE

Determination of Damping

1. The test bar with the applied damping treatment was suspended
horizontally from an edge of the bar by means of ropes, at two attach-
ment points. An electromagnetic vibrator, which served to excite vibra-
tions in the test assembly, was connected to one end of the bar, and
an accelerometer to the other end. The bar and these attachments were
placed in a constant–temperature room which was maintained at either
85° or 95°F. The instrumentation used is schmatically shown in
Appendix 4.

2. Damping was determined as follows: the frequency of the vibrator
was gradually increased until the response of the pickup indicated a
response frequency for the bar assembly. The drive to the vibration
exciter was then shut off by means of a relay, and the decaying vibration
of the test bar, as detected by the accelerometer, was displayed on the
Memoscope. The attenuation angle of the logarithm of the amplitude
signal, A, to the horizontal coordinate was measured. Damping, expressed
as per cent of the critical damping, was calculated according to the
following formula:

$$\text{Per cent of critical damping} = \frac{K \tan A}{TF}$$

I

Where:

      K = a constant containing calibration factors
          of the instruments used.

      T = the sweep time of the Memoscope, in seconds.

      F = the vibration frequency of the test bar in
          cycles/second.

3. Damping of resonance frequencies up to about 3000 cps were measured.
Beyond this range wide gaps existed between the detected resonance
frequencies, and the signals were, in general, very weak. Spot checks
indicated that damping was also low, about 1%, or less.

Checking of Damping Measurements

4. The instrument system shown in Appendix 4 was checked at least once
daily by means of the electrical analog which was described in
reference (j). An analog having an inductance of 0.02 henrys, a capaci-
tance of 0.97 microforads, and a resonance frequency of 1137 cps was
used in most tests. A few spot checks were also made periodically with
the same instrument using, however, a 0.2 microforad capacitor. The
resonance frequency of this arrangement was 2510 cps. There were no
significant differences between the results obtained with the two arrange-
ments.

5. The damping in this type of analog is proportional to the resistance
of the apparatus, according to the following relation:

$$\frac{C}{C_c} = \frac{R}{2} \sqrt{\frac{B}{L}}$$

II

Where:

> C = damping of electric discharge
>
> C_c = critical damping of electrical circuit
>
> R = resistance of apparatus in ohms
>
> B = capacitance in farads
>
> L = inductance in henrys

6. In each check test the resistance was varied over a wide range, and the measured damping of the electrical signal after passing through the filter, the log amplifier, and the Memoscope was compared with the damping calculated according to the above equation. In general, there was a fair agreement between the calculated and the observed damping up to about 15-18%. Above this range there was often poor reproducibility in the measured damping values, and on the whole, the latter tended to be about 10% to 20% below the calculated values. This behavior indicates that the measured damping values of the treatment assemblies above about 15% or 18% of critical were likely to have been smaller than the actual damping.

Identification and Selection of Flexural Modes of Vibration

7. Reference (k) stated that it was essential that the flexural modes be positively identified, and that the modes of vibration be of the same type in all compared frequencies. This was done by plotting the observed resonance frequencies on a log-log graph paper, against the flexural mode number, n. The observed frequencies were assigned the consecutive (n + 0.5) values. A straight line of best fit was drawn through the points, and the frequencies which significantly deviated from this

III

line were eliminated as being due to vibrational modes other than those under study. The basis for this procedure had been explained in reference (h).

8. There was, in general, a very close linear relation between log (n + 0.5) and log frequency for n values up to about 8 or 10, and very few points had to be eliminated in this range. Beyond this point spurious frequencies were often encountered. The above method for frequency identification was quite reliable for frequencies up to about 2000 cps, but became progressively less reliable beyond this range.

Application and Determination of Constraining Pressure

9. The damping treatments were subjected to constraining pressures by applying torques to the nuts of the supporting studs by means of torque wrenches. A definite torque was applied in each case, the assembly was then let stand for 10 to 30 minutes, after which the torque was adjusted again to the original value. The assembly was then ready for damping measurements. Conversion of a torque to its corresponding constraining pressure was by means of the following formula:

$$P = \frac{T}{0.2 \text{x} D \text{x} A}$$

Where:

P = constraining pressure, in psi

T = applied torque, in inch-lbs

D = stud diameter, in inches

A = area of constraining aluminum layer per stud, in square inches

IV

10. The formula on the preceeding page is based on the expression $T = 0.2 \times D \times L$ given in reference (1). In this expression L is the initial tension in pounds induced in a bolt by the application of a torque, T, to the securing nut. D is the bolt diameter.

11. There was a rapid stress relaxation in the constraining layer following the application of torque. This relaxation continued during the period of damping measurements. The constraining pressure calculated from the above formula represents only the initial constraining pressure, and not the actual pressure during the damping determinations. All of the constraining pressure data in this report refer to the initial pressure, unless otherwise specified. The effect of pressure on damping was mainly due to the degree of compression of the felt. The nuts of the studs were not disturbed during the damping test, and thus the degree of compression of the felt remained unchanged during this period.

12. The amount of felt compression by a given torque was not constant. It varied with the rate of torque application, with the length of the time interval between torque application and adjustment, and possibly also with stud spacing.

Determinations of Thickness of Compressed Felt and Bulging of Constraining Layer

13. Thickness of the felt layer in the treatment assembly after it had been subjected to a constraining pressure was determined by measuring the thickness of the assembly with a micrometer calibrated in 0.001-inch units. Similar measurements were made also on the assembly without

V

3

the felt. The difference between the two thicknesses corresponded to
the felt thickness. When the damping treatments were applied to the two
sides of the steel bar, one 1/8 inch felt layer, on each side, the
difference between the two measured thicknesses was divided by 2.
No such division was made when the treatment was applied to only one
side of the bar. The felt thickness values given in the tables refer
to felt strips of a nominal thickness of 1/8 inch in the uncompressed
state.

14. From 15 to about 30 thickness measurements were made on each bar
and averaged. These measurements were taken at regularly distributed
points on the bar. They were taken near the edge of the bar at points
lying above the studs, as well as half way between studs. Measurements
were taken, whenever possible, also along the middle of the treatment's
face, along the line connecting the studs.

15. These measurements served also to establish the presence or absence
of bulging in the constraining layer, as well as the magnitude of the
bulge.

Determination of True Specific Gravity of Treated Felt

16. The specific gravity of the solid materials in the felt was
determined in order to calculate the volume of the air interstices in
the compressed felt layer of the damping treatment. This determination
was performed in the following manner: a non-compressed felt sample was
first weighed in air. The sample was then submerged in water in a glass
container, and the container was evacuated continuously for one hour to

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remove the air from the felt. A trace of n-heptyl alcohol was added to
the water to reduce surface tension, and accelerate the removal of the
air bubbles. The sample was then weighed again under water. The specific
gravity, S_c, of the felt material, after removal of air was 1.505. The
thickness of the felt strip compressed to the point when all air inter-
stices have been eliminated, assuming that no lateral expansion of the
felt took place during compression, was designated by T_c.

17. From the thickness of a felt sample of a known area , prior to
compression, T_a, and its weight in air, the specific gravity of the
sample in this condition, S_a, was determined. From these quantities
T_c was calculated by means of the following relation:

$$T_c = \frac{T_a \times S_c}{S_a}$$

Determination of Air Space in Felt

18. The above equation enables the calculation of the volume fraction
of air in the felt, F, at any state of compression, from the following
relation:

$$F = \frac{V_f - V_c}{V_f}$$

Where:

V_f = volume of compressed felt, including air space

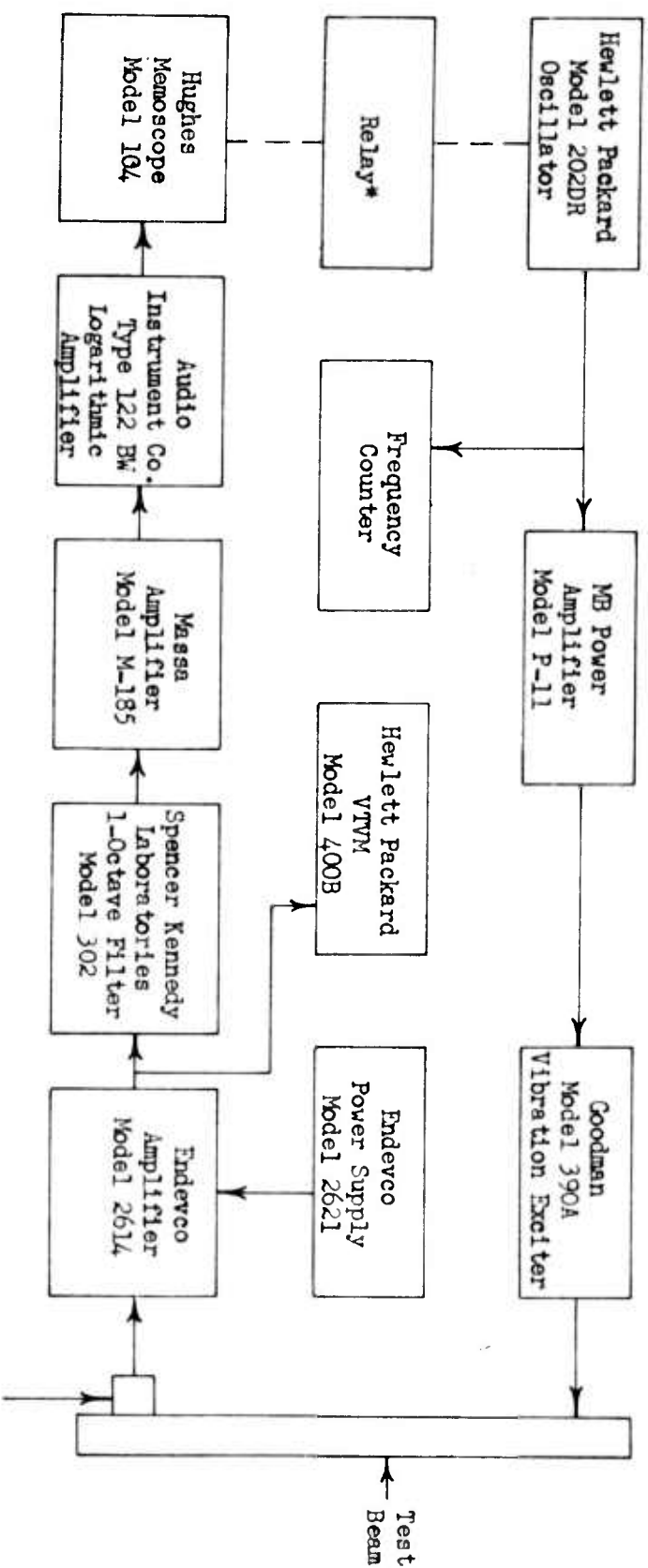V_c = volume of solid felt material without air space

VII

19. For a felt sample of a given area, A, and a thickness, T, the following relations hold:

$$V_f = AT$$

$$V_c = AT_c$$

$$F = \frac{AT - AT_c}{AT} = \frac{T - T_e}{T}$$

VIII

3

SCHEMATIC LAYOUT OF INSTRUMENTATION USED TO DETERMINE DAMPING

Hewlett Packard Model 202DR Oscillator

Relay*

Hughes Memoscope Model 104

Audio Instrument Co. Type 122 BW Logarithmic Amplifier

Frequency Counter

MB Power Amplifier Model P-11

Massa Amplifier Model M-185

Hewlett Packard VTVM Model 400B

Spencer Kennedy Laboratories 1-Octave Filter Model 302

Goodman Model 390A Vibration Exciter

Endevco Amplifier Model 2614

Endevco Power Supply Model 2621

Massa Accelerometer Model 198

Test Beam

* Relay interrupts output of oscillator and simultaneously triggers scope.

4

Treatment 178A

Frequency cps	Per Cent Critical Damping				Freque cps
	Run 1	Run 2	Run 3	Run 4	
55	10.2	11.5	10.2	11.1	4
128	11.3	10.8	11.6	13.7	10
220	12.2	12.5	12.1	12.4	19
334	13.9	13.2	12.6	11.9	30
479	10.5	11.6	10.7	10.9	43
637	11.2	10.9	9.3	9.9	59
817	7.5	8.4	8.1	9.1	77
1035	8.5	6.5	7.2	7.1	98
1226	2.5	3.2	5.3	6.2	120
1451	8.2	6.3	4.4	1.0	143
1741	5.4	5.0	5.0	6.1	167
1955	2.4	1.6	2.1	1.4	189
2236	1.1	0.6	1.1	1.0	223

Average per cent of critical damping
over frequency range for each run   8.1   7.9   7.7   7.8

Mean per cent of critical damping
over frequency range for four runs   7.9

VARIABILITY OF DAMPING VALUES IN REPLICATE TEST RUNS ON SAME ASSEMBLIES

| Frequency cps	Treatment 178A Per Cent Critical Damping				Frequency cps	Treatment 179A Per Cent Critical Damping			
	Run 1	Run 2	Run 3	Run 4		Run 1	Run 2	Run 3	Run 4
55	10.2	11.5	10.2	11.1	43	9.0	8.2	7.8	8.4
128	11.3	10.8	11.6	13.7	103	11.6	10.5	10.6	10.3
220	12.2	12.5	12.1	12.4	191	9.2	10.4	10.2	9.5
334	13.9	13.2	12.6	11.9	305	8.0	11.1	9.3	9.1
479	10.5	11.6	10.7	10.9	437	8.1	8.0	7.8	8.0
637	11.2	10.9	9.3	9.9	598	4.6	6.7	7.1	6.9
817	7.5	8.4	8.1	9.1	775	3.8	5.5	5.7	5.0
1035	8.5	6.5	7.2	7.1	988	3.6	6.2	4.9	4.5
1226	2.5	3.2	5.3	6.2	1202	3.9	5.3	5.3	6.0
1451	8.2	6.3	4.4	1.0	1433	2.8	3.9	4.6	3.5
1741	5.4	5.0	5.0	6.1	1671	1.3	3.8	3.3	4.3
1955	2.4	1.6	2.1	1.4	1899	–	3.4	2.6	3.3
2236	1.1	0.6	1.1	1.0	2234	0.8	0.7	0.6	0.8
damping run	8.1	7.9	7.7	7.8		5.6	6.4	6.1	6.1
ping runs		7.9					6.1		
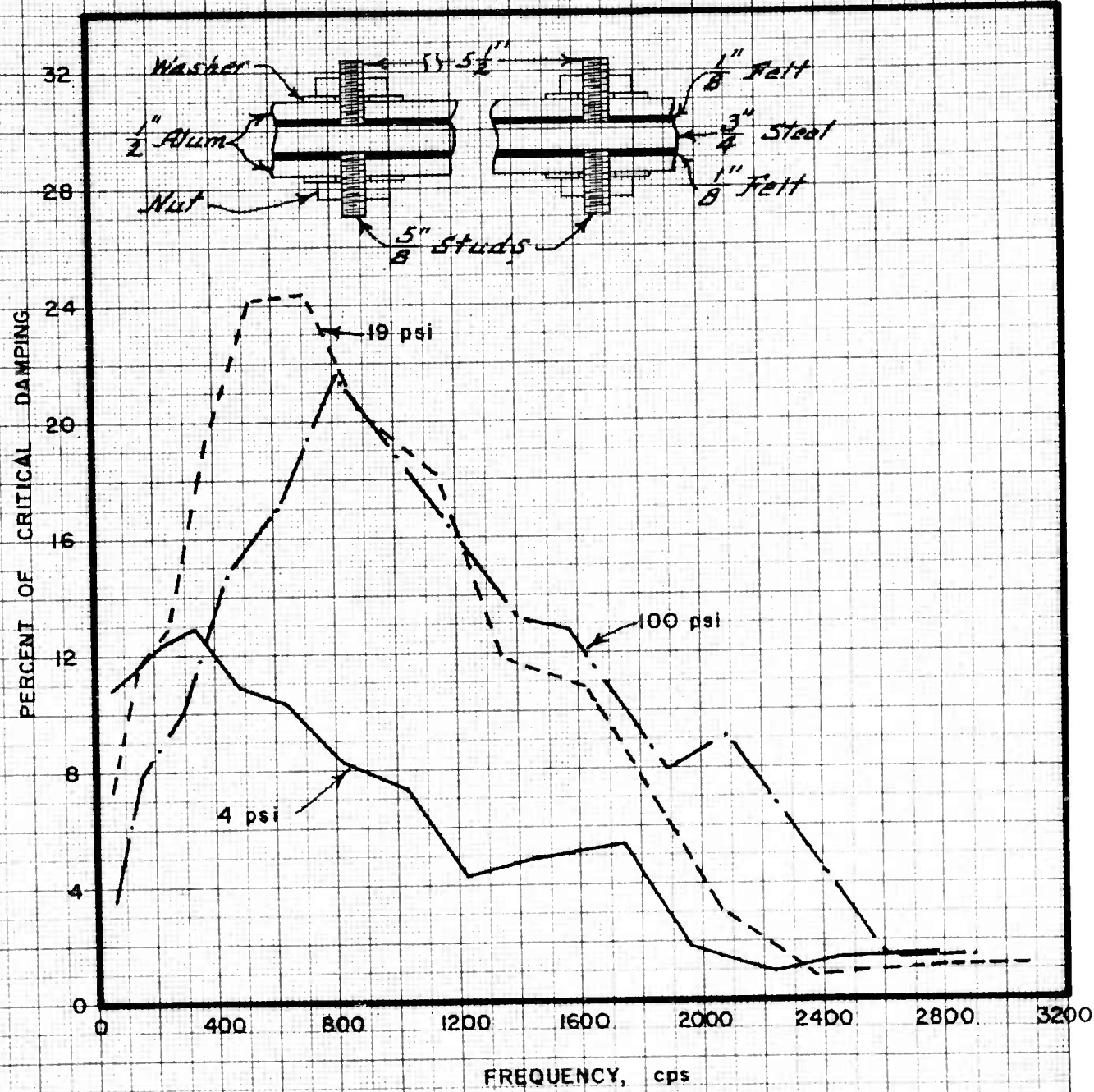
EFFECT OF CONSTRAINING PRESSURE ON DAMPING OVER FREQUENCY RANGE BY TREATMENT 178A
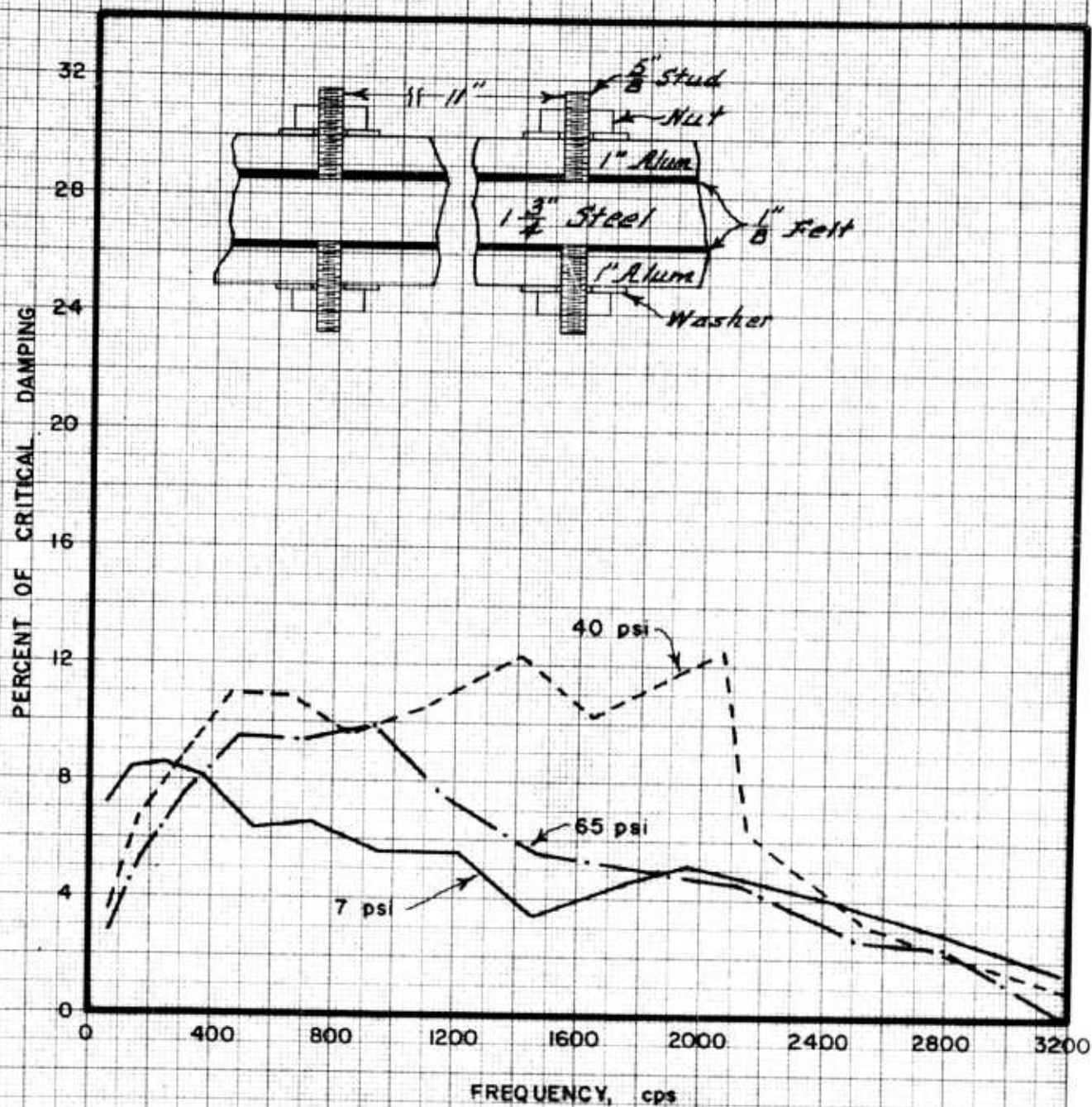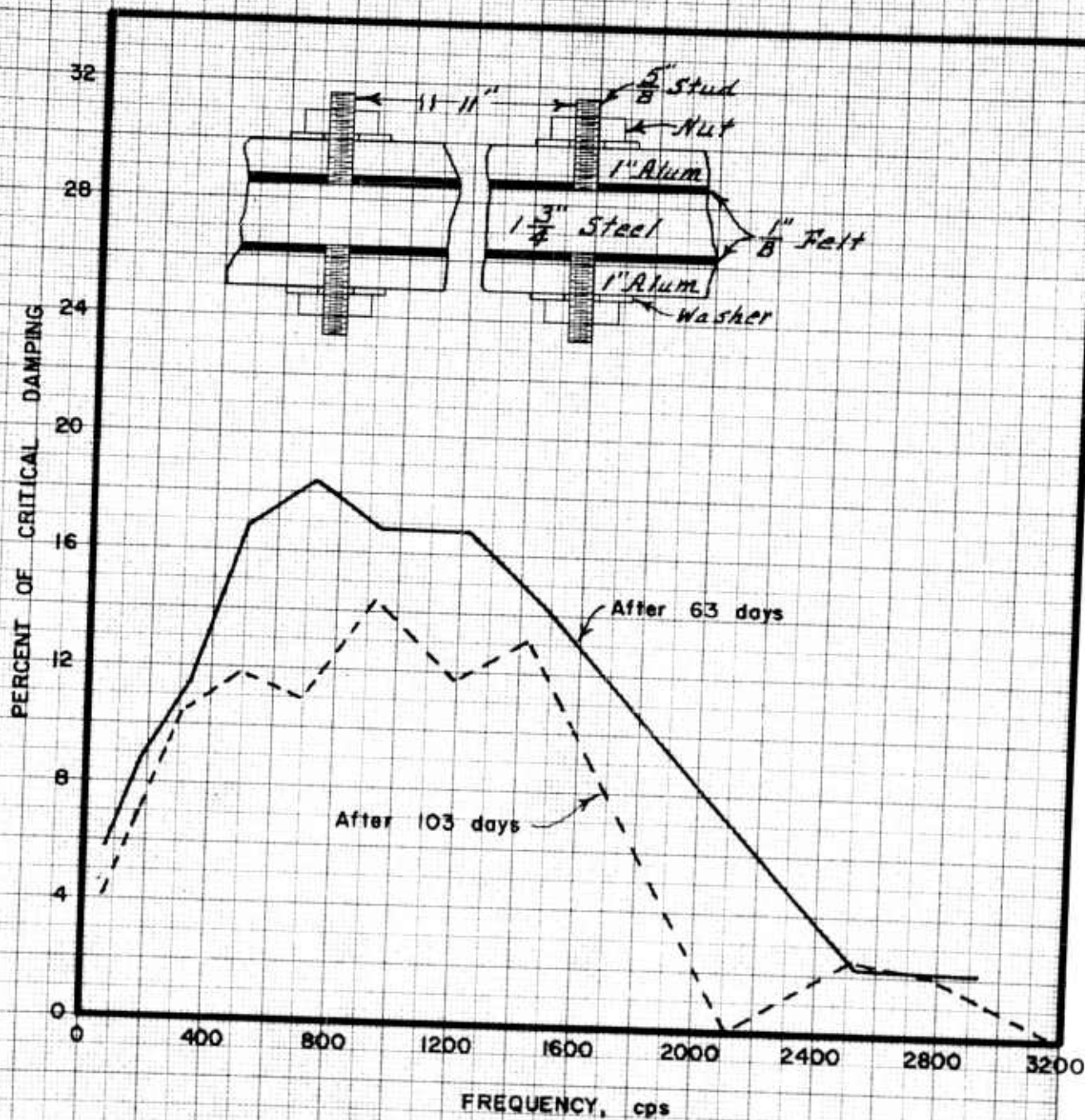
EFFECT OF CONSTRAINING PRESSURE ON DAMPING OVER FREQUENCY RANGE BY TREATMENT 170
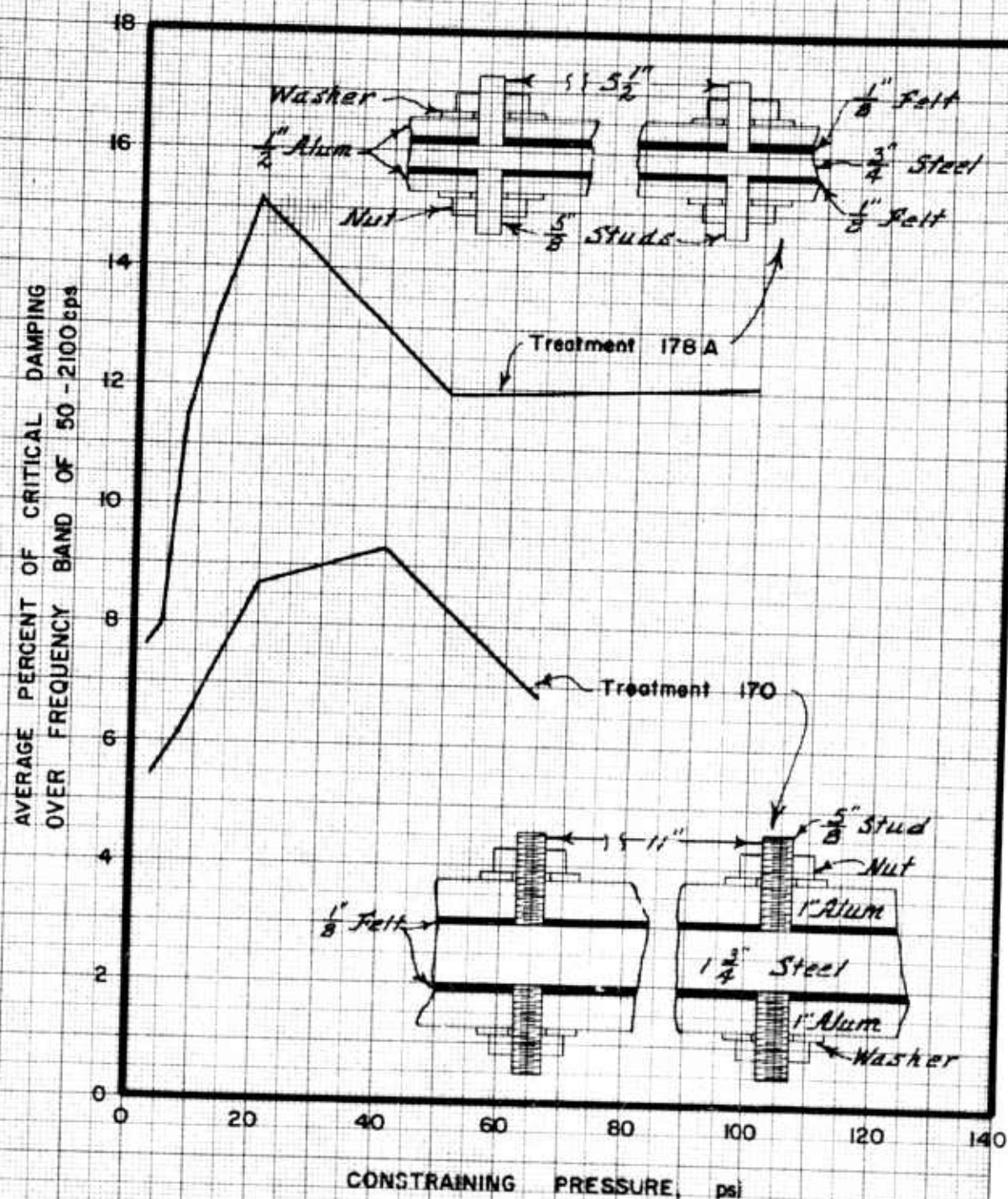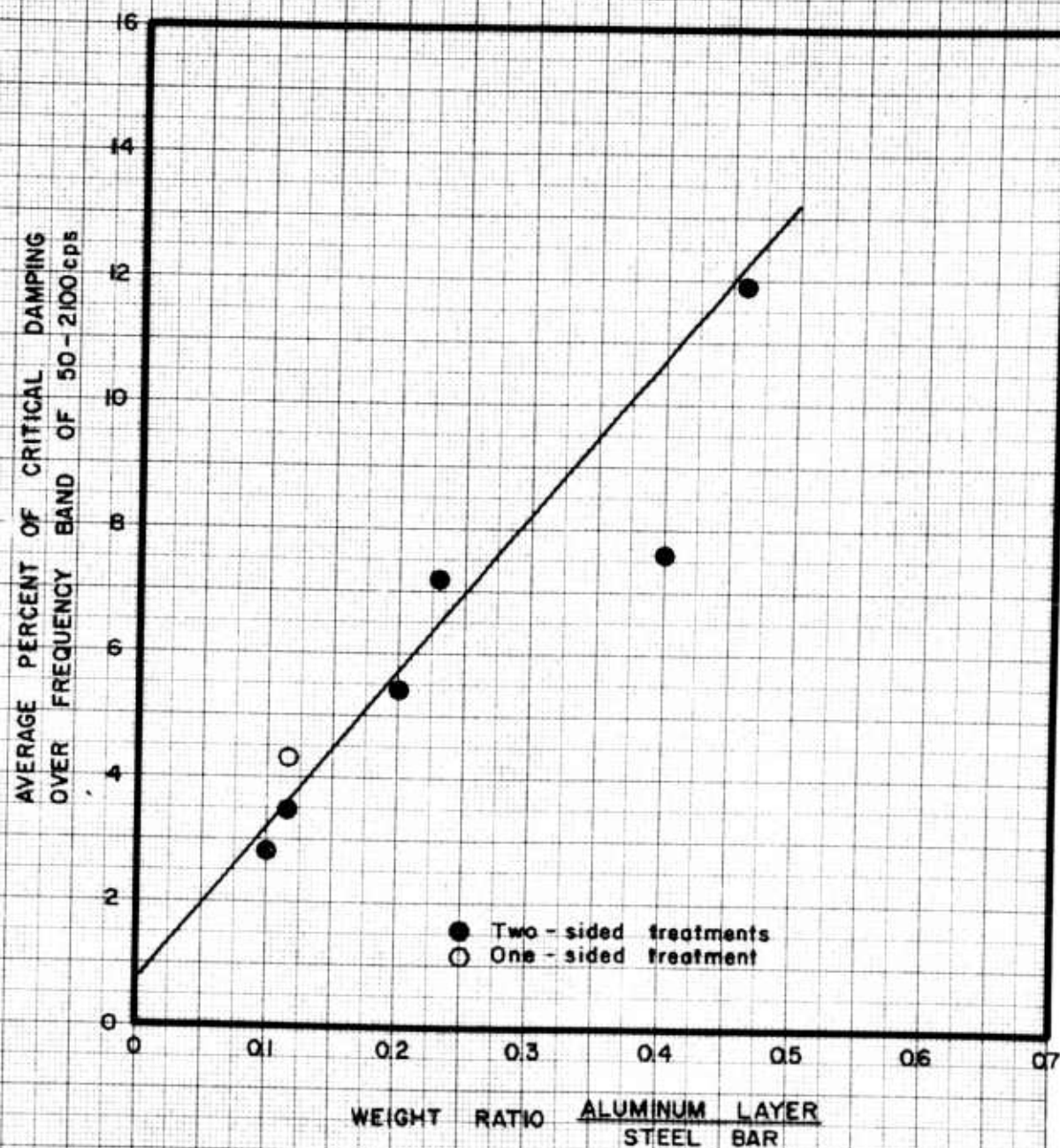
EFFECT OF CONSTRAINING PRESSURE ON AVERAGE DAMPING BY TREATMENTS 178A AND 170
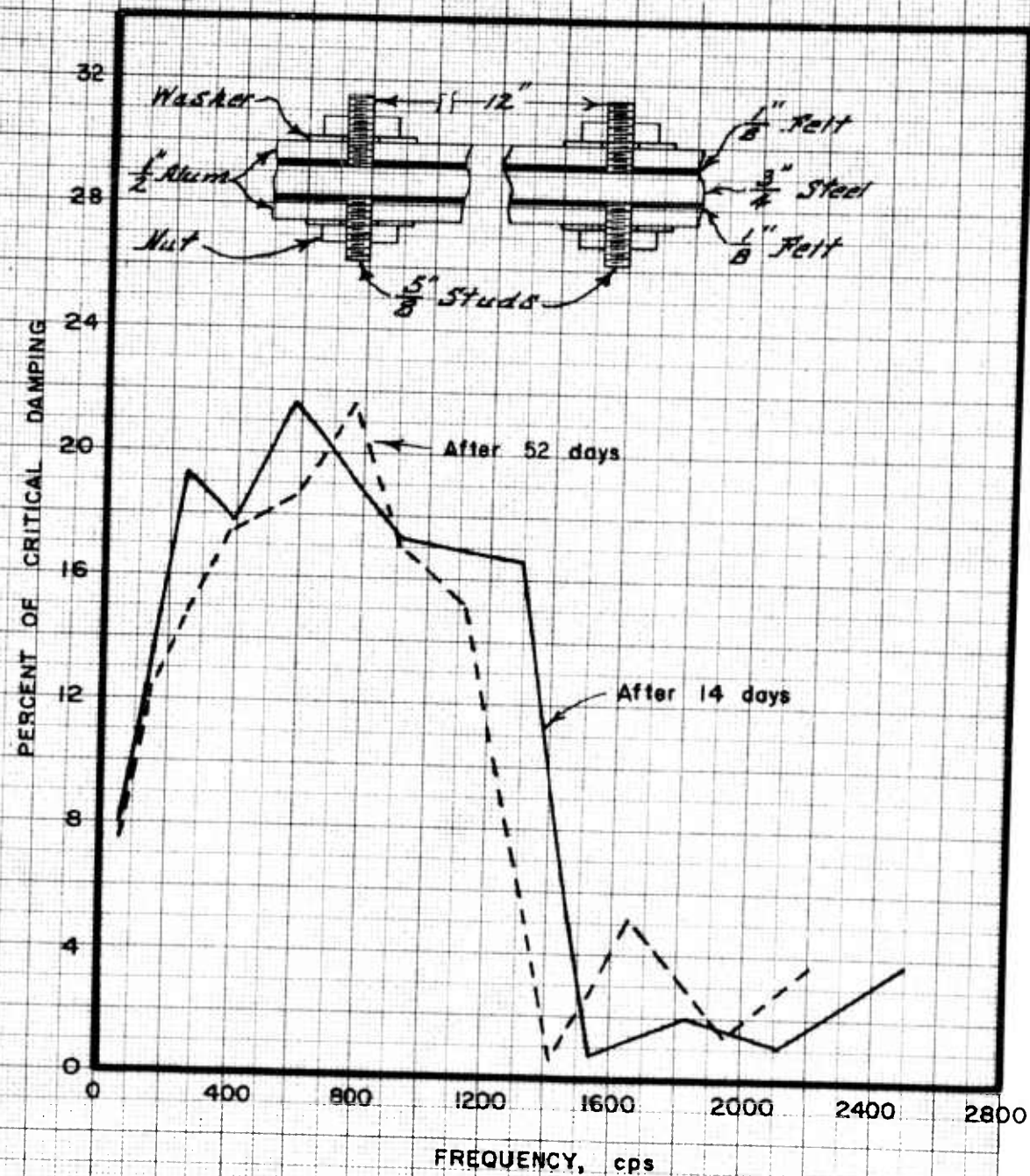
DAMPING OVER FREQUENCY RANGE BY TREATMENT 178
AFTER PROLONGED RELAXATION OF CONSTRAINING PRESSURE

9

DAMPING OVER FREQUENCY RANGE BY TREATMENT 170
AFTER PROLONGED RELAXATION OF CONSTRAINING PRESSURE

10

AVERAGE DAMPING AND WEIGHT RATIO OF ALUMINUM CONSTRAINING
LAYERS TO STEEL BAR AT A CONSTRAINING PRESSURE OF 50 PSI